The History and Future of Ocean Acidification in the California Current Ecosystem

Emily B. Osborne
Knauss Fellow, NOAA OAR/CPO Arctic Research Program

Robert C. Thunell[1], Nicholas Gruber[2], Richard A. Feely[3], Claudia Benitez-Nelson[1], Wei-Jun Cai[4], Jessica Holm[1], Brittney Marshall[1]

[1]School of the Earth, Ocean and Environment, University of South Carolina, Columbia, South Carolina, USA
[2]Environmental Physics, Institute of Biogeochemistry and Pollutant Dynamics, ETH Zürich, Zürich, Switzerland.
[3]Pacific Marine Environmental Laboratory/National Oceanic and Atmospheric Administration, Seattle, Washington, USA.
[4]College of Earth, Ocean, and Environment, University of Delaware, Newark, Delaware, USA

Photo Credit: Ethan Daniels

Anthropogenic CO_2 Sources

+69 ppm
Land Use Change

+5 ppm
Cement Production

+184 ppm
Fossil Fuel

CO_2
Carbon Dioxide Gas

288 ppm CO_2
Preindustrial Atmospheric Concentration

400 ppm CO_2
Modern Atmospheric Concentration

Anthropogenic CO_2 Sinks

+258 ppm
Anthropogenic CO_2

-110 ppm
Atmospheric Sink

-73 ppm
Ocean Sink

-75 ppm
Terrestrial Sink

CO_2 + H_2O ⟷ H^+ + HCO_3^-

Dissolved Carbon Dioxide

Hydrogen Ion

Bicarbonate Ion

pH 0.1

HCO^{3-} ⟷ H^+ + CO_3^{2-}

Bicarbonate Ion

Hydrogen Ion

Carbonate Ion

Relative Shifts in the Marine Carbonate System

↑ DIC = ↑ HCO_3^- + ↓ CO_3^{2-}

Dissolved Inorganic Carbon

<1%
CO_2
Dissolved Carbon Dioxide

+

~80%
Bicarbonate Ion

+

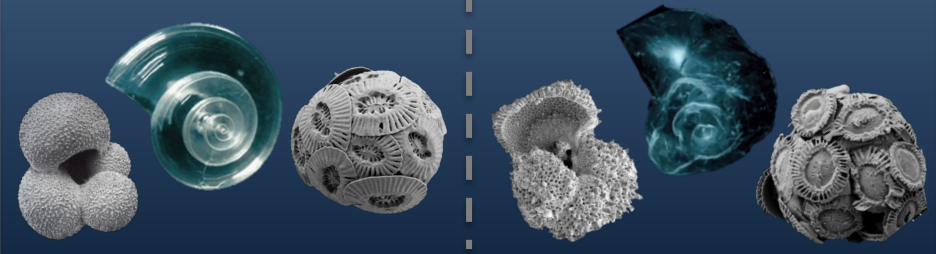
~20%
Carbonate Ion

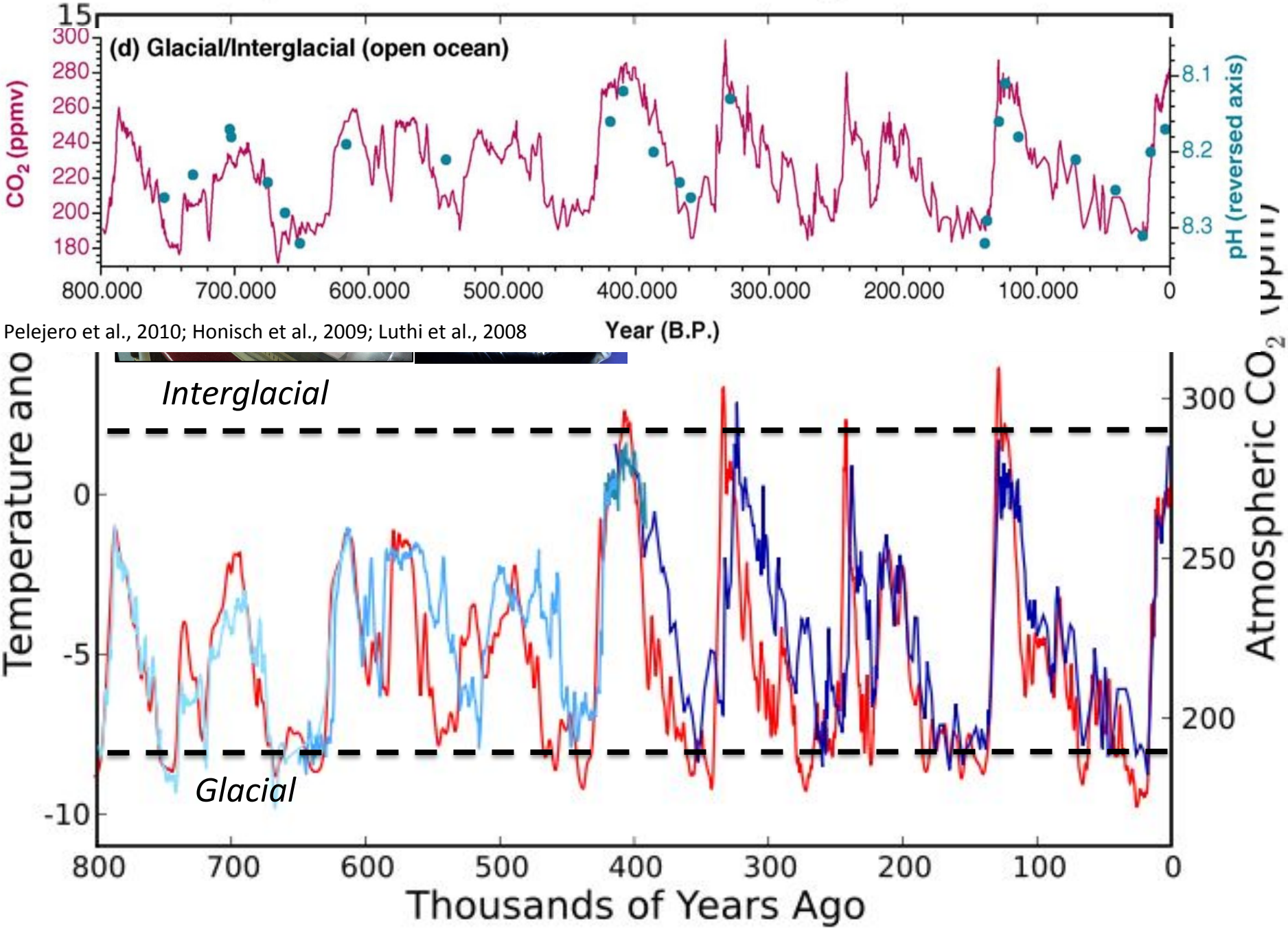
Calcification by Marine Organisms

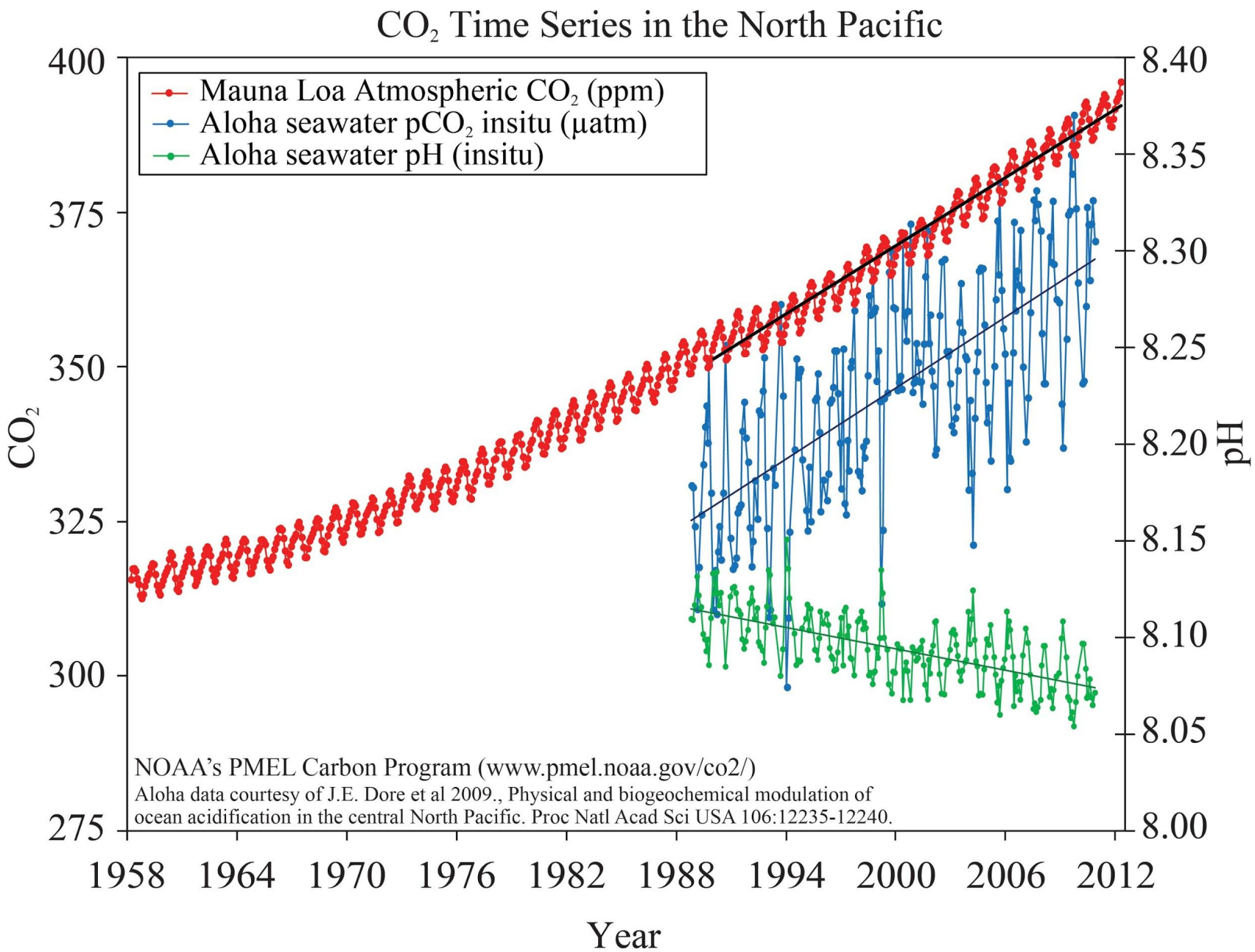
$CaCO_3$
Calcium Carbonate

↑ CO_3^{2-}
Carbonate Ion

↓ CO_3^{2-}
Carbonate Ion

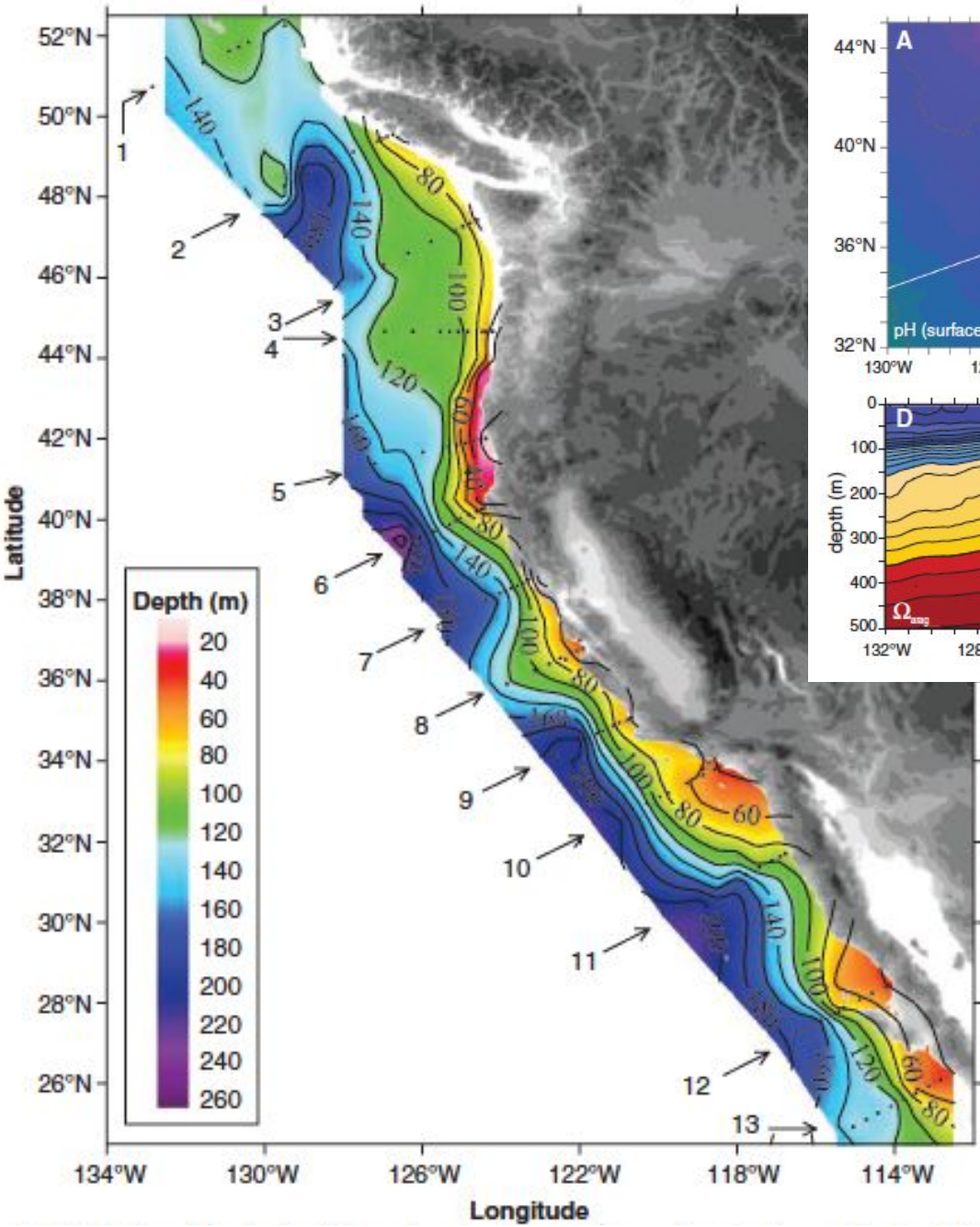



(d) Glacial/Interglacial (open ocean)
CO2 (ppmv)
pH (reversed axis)
Year (B.P.)
Pelejero et al., 2010; Honisch et al., 2009; Luthi et al., 2008
Interglacial
Glacial
Temperature ano
Atmospheric CO2 (ppmv)
Thousands of Years Ago


CO2 Time Series in the North Pacific
Mauna Loa Atmospheric CO2 (ppm)
Aloha seawater pCO2 insitu (µatm)
Aloha seawater pH (insitu)
400
375
350
325
300
275
CO2
8.40
8.35
8.30
8.25
8.20
8.15
8.10
8.05
8.00
pH
1958
1964
1970
1976
1982
1988
1994
2000
2006
2012
Year
NOAA's PMEL Carbon Program (www.pmel.noaa.gov/co2/)
Aloha data courtesy of J.E. Dore et al 2009., Physical and biogeochemical modulation of ocean acidification in the central North Pacific. Proc Natl Acad Sci USA 106:12235-12240.

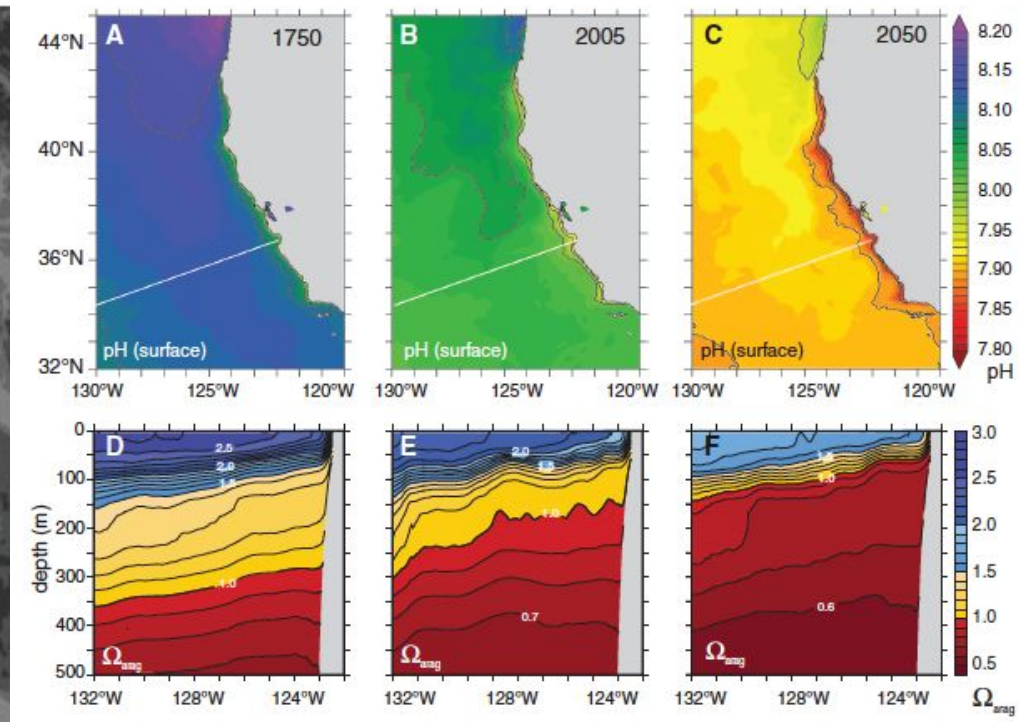
Observations

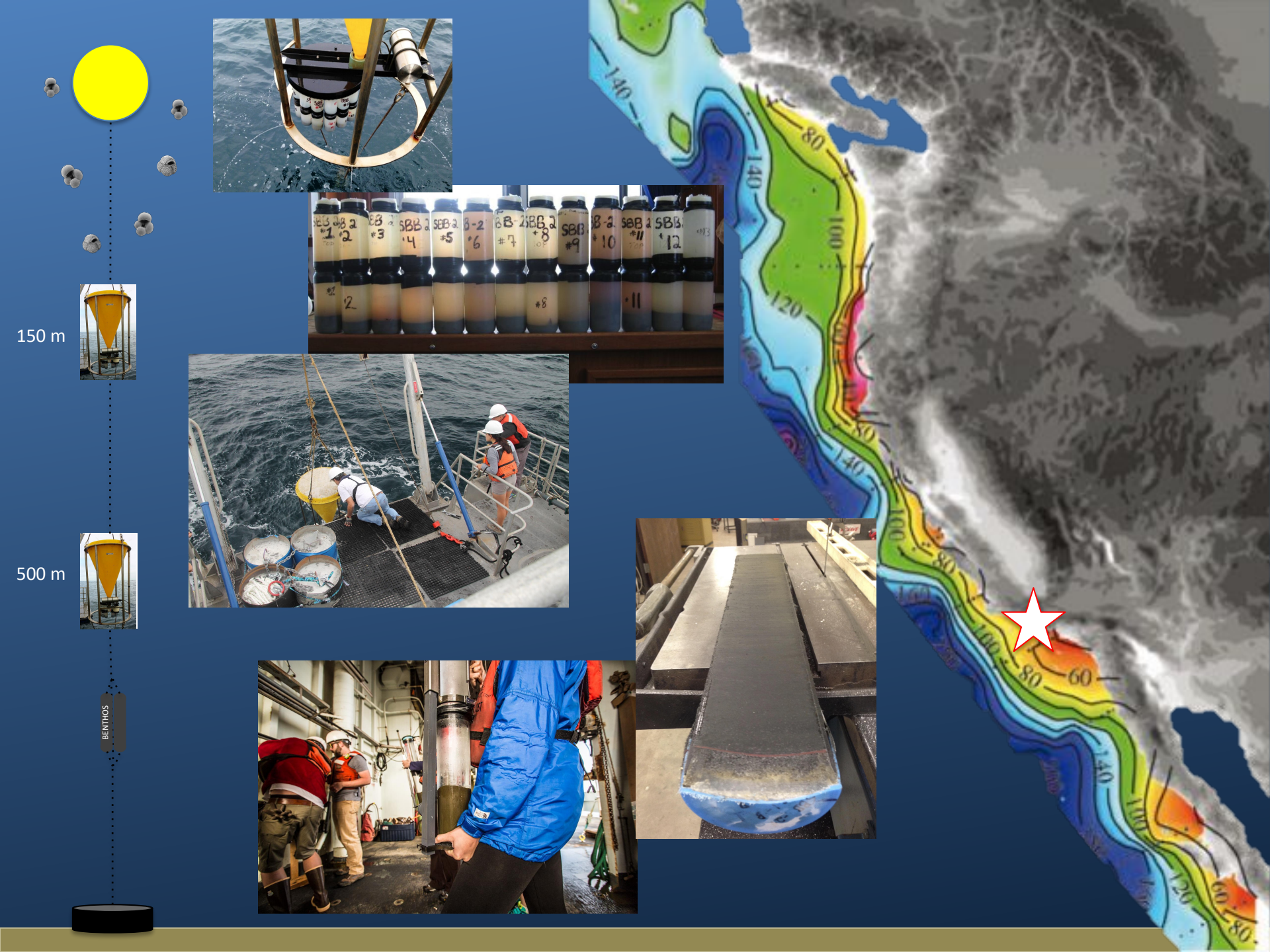
Feely et al., 2008



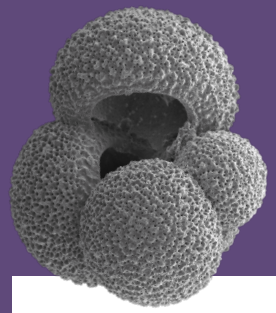
Model Simulations

Gruber et al., 2012




150 m
500 m
BENTHOS

Calibrating the Calcification Response of *G. bulloides* to $[CO_3^{2-}]$



AGU PUBLICATIONS

Paleoceanography

RESEARCH ARTICLE
10.1002/2016PA002933

Key Points:
- *G. bulloides* calcification intensity is primarily controlled by ambient seawater $[CO_3^{2-}]$, while size is related to calcification temperature
- The relationship between calcification intensity and $[CO_3^{2-}]$ can be used for past reconstructions of $[CO_3^{2-}]$
- Morphospecies of G. bulloides found in the Southern California Bight can be identified using shell area density

Supporting Information:
- Supporting Information S1
- Data Set S1
- Data Set S2

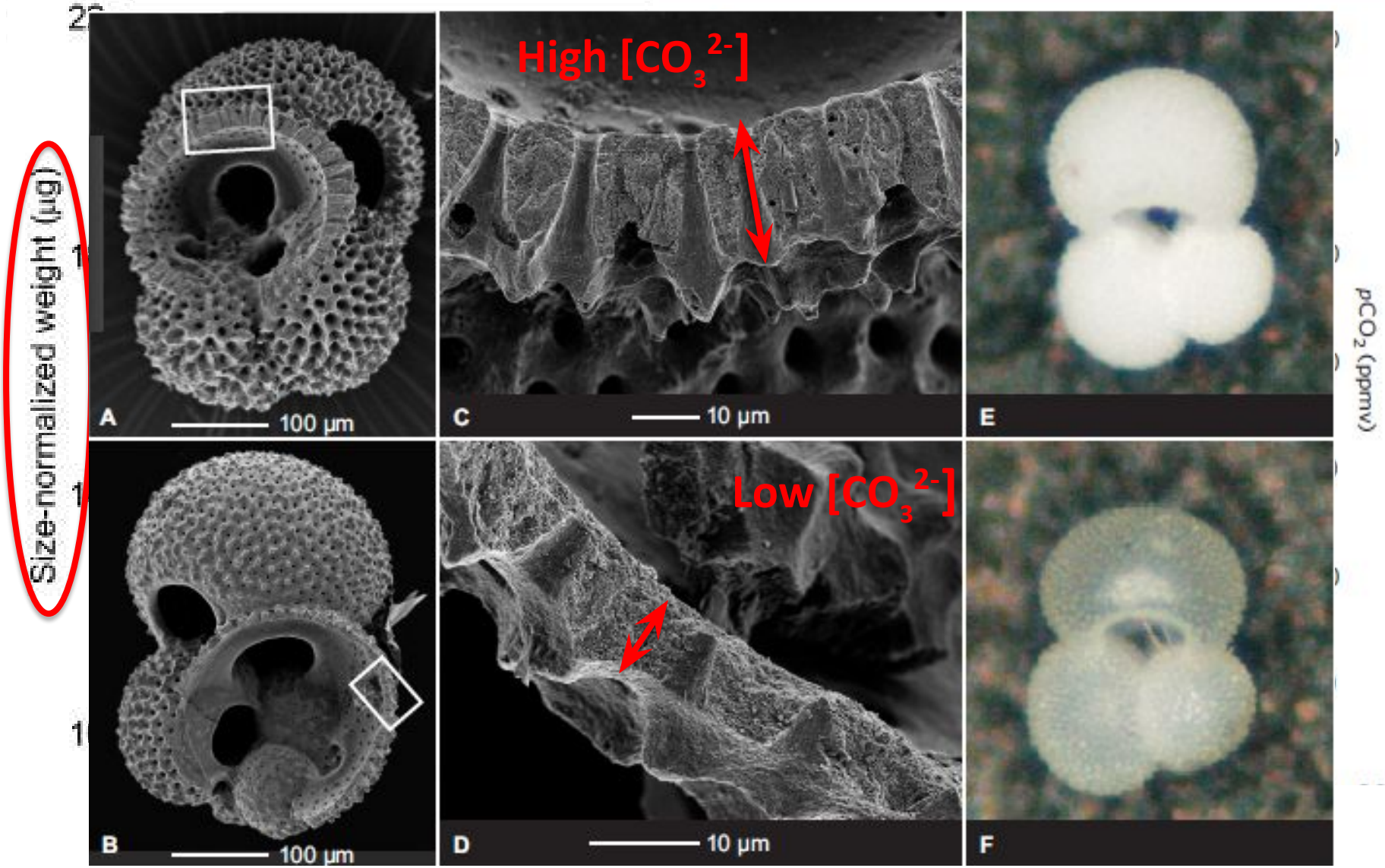
Calcification of the planktonic foraminifera *Globigerina bulloides* and carbonate ion concentration: Results from the Santa Barbara Basin

Emily B. Osborne[1], Robert C. Thunell[1], Brittney J. Marshall[1], Jessica A. Holm[1], Eric J. Tappa[1], Claudia Benitez-Nelson[1], Wei-Jun Cai[2], and Baoshan Chen[2]

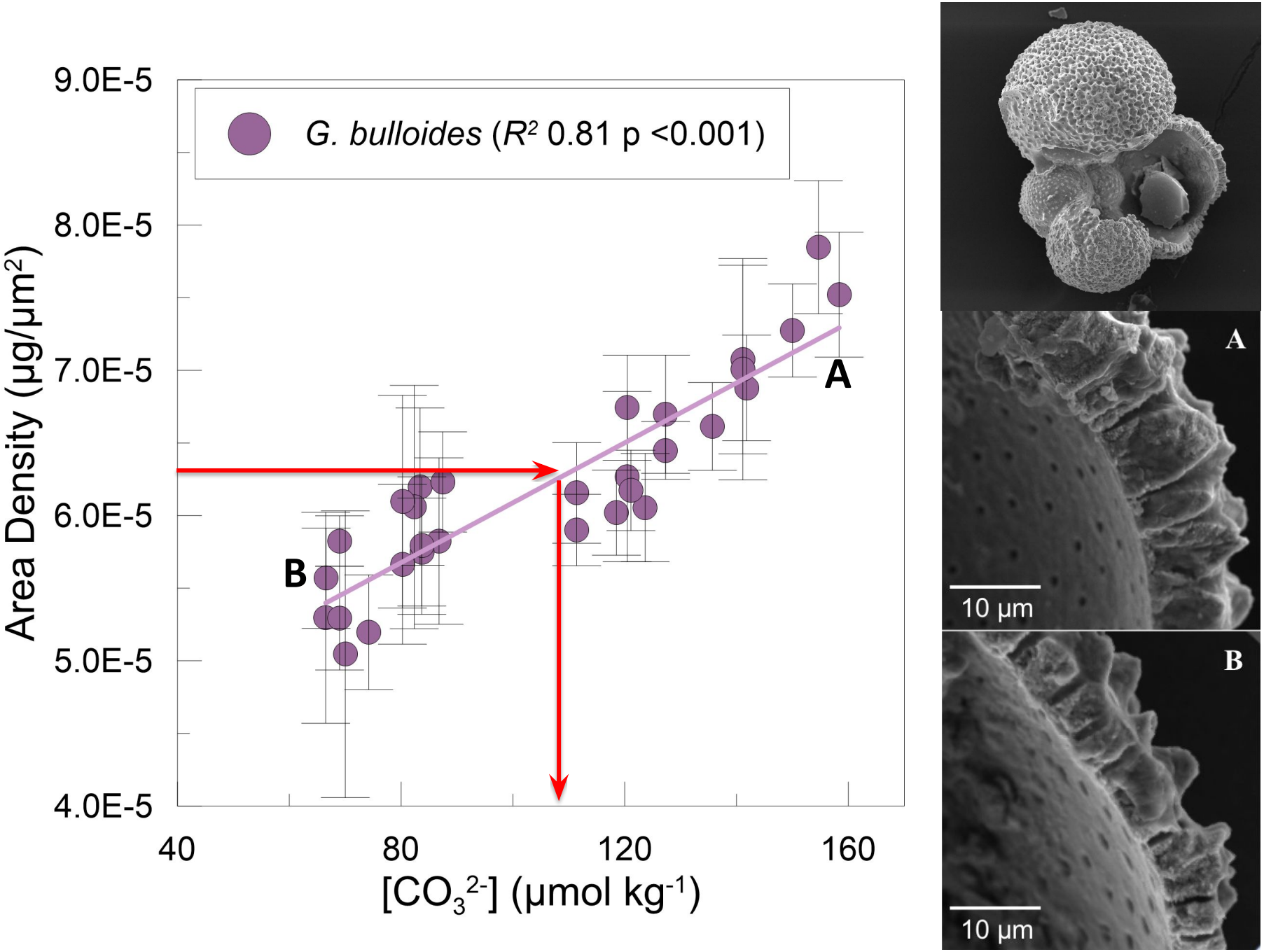
[1]School of the Earth, Ocean, and Environment, University of South Carolina, Columbia, South Carolina, USA, [2]College of Earth, Ocean, and Environment, University of Delaware, Newark, Delaware, USA

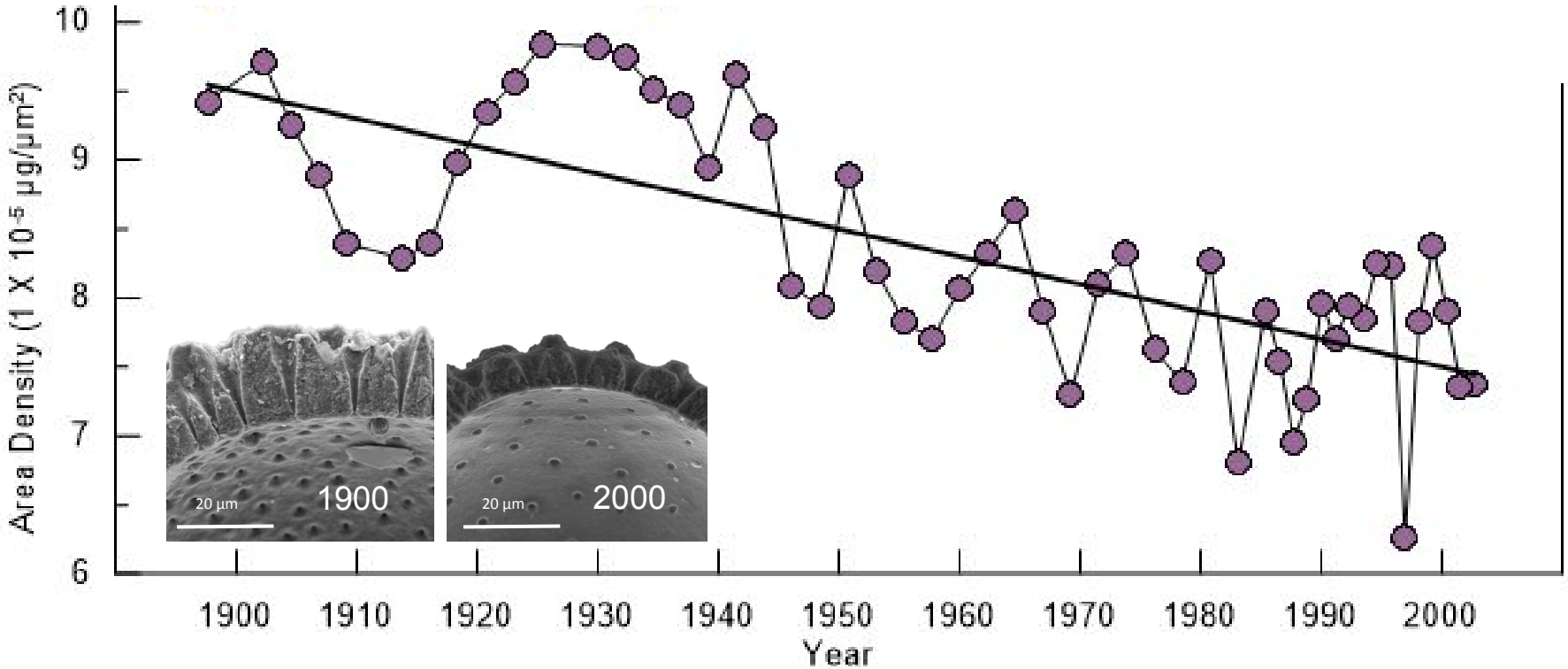
Abstract Planktonic foraminiferal calcification intensity, reflected by shell wall thickness, has been hypothesized to covary with the carbonate chemistry of seawater. Here we use both sediment trap and box core samples from the Santa Barbara Basin to evaluate the relationship between the calcification intensity of the planktonic foraminifera species *Globigerina bulloides*, measured by area density ($\mu g/\mu m^2$), and the carbonate ion concentration of seawater ($[CO_3^{2-}]$). We also evaluate the influence of both temperature

Planktonic Foraminifera Shell Weight



Barker & Elderfield, 2002

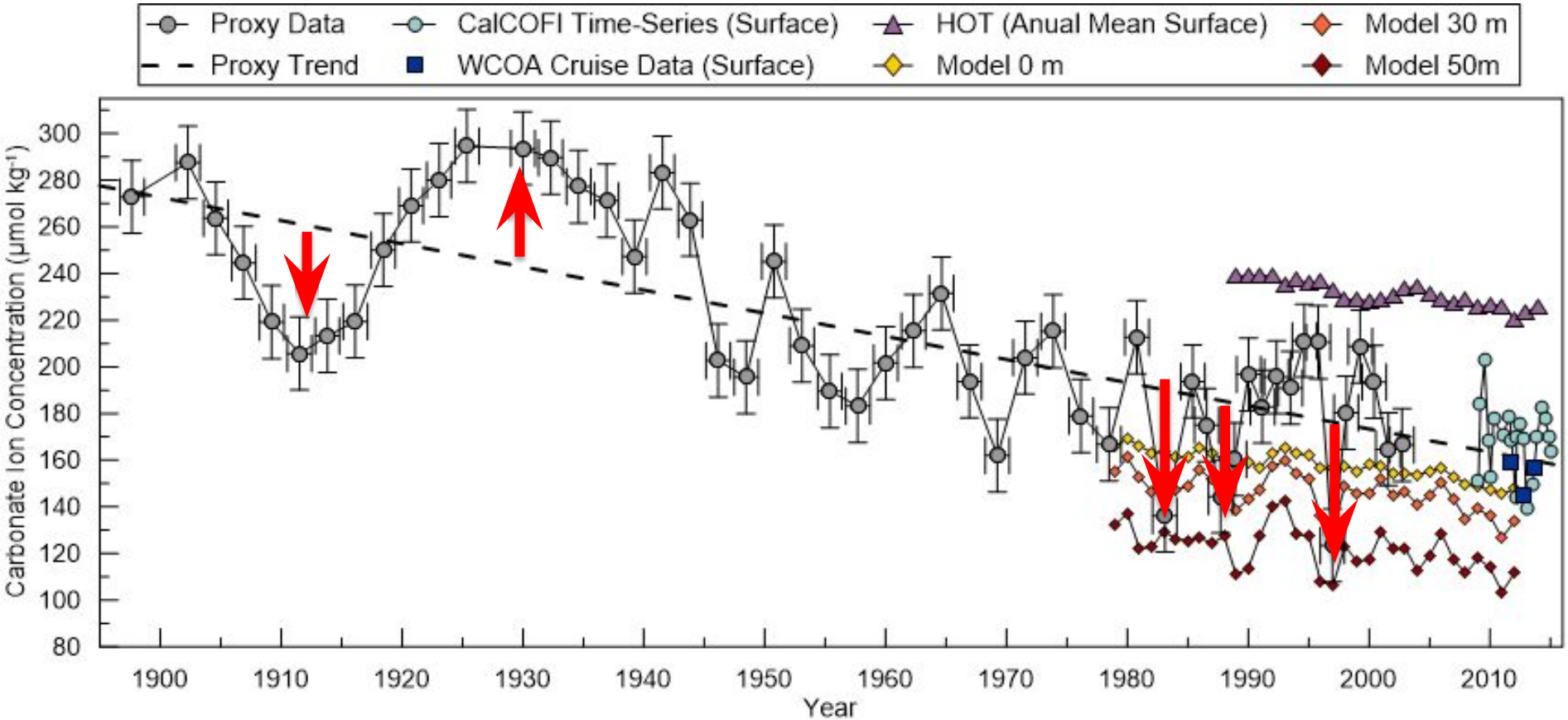

G. bulloides (R² 0.81 p <0.001)
Area Density (µg/µm²)
9.0E-5
8.0E-5
7.0E-5
6.0E-5
5.0E-5
4.0E-5
40
80
120
160
[CO3 2-] (µmol kg-1)
A
B
10 µm
10 µm



Area density and shell diameter measurements indicate that *G. bulloides* produced **20% thinner and 7% larger shells**, respectively, over the 21st century.

35% decline in surface ocean [CO_3^{2-}] over the 20th century

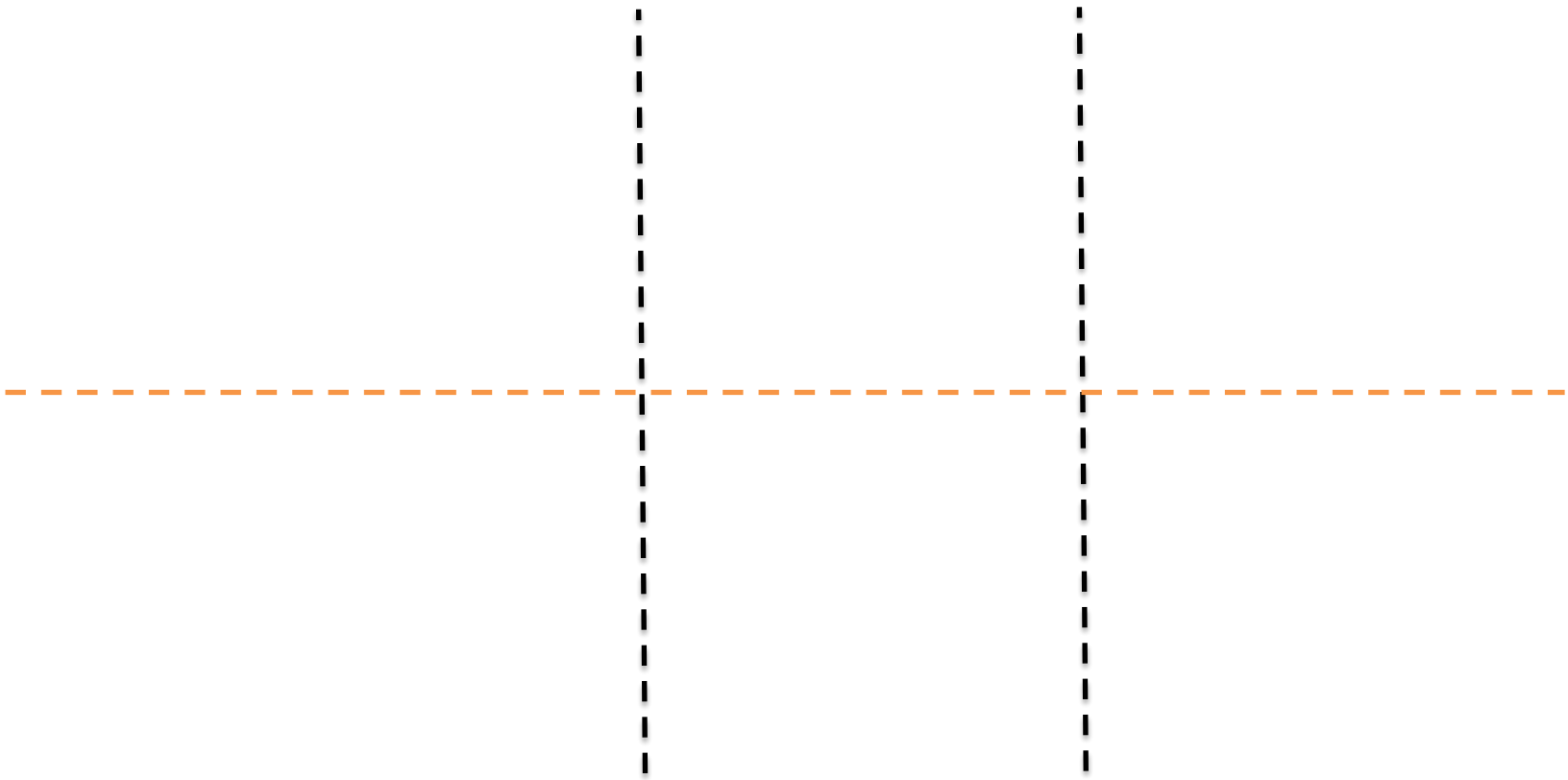
(271 to 173 ±16 µmol kg^{-1}) or nearly a 100 µmol kg^{-1} change



translating to a 0.25 unit decline in pH in this region (8.17-7.92), thereby exceeding the global average of 0.1 units by more than a factor of two.

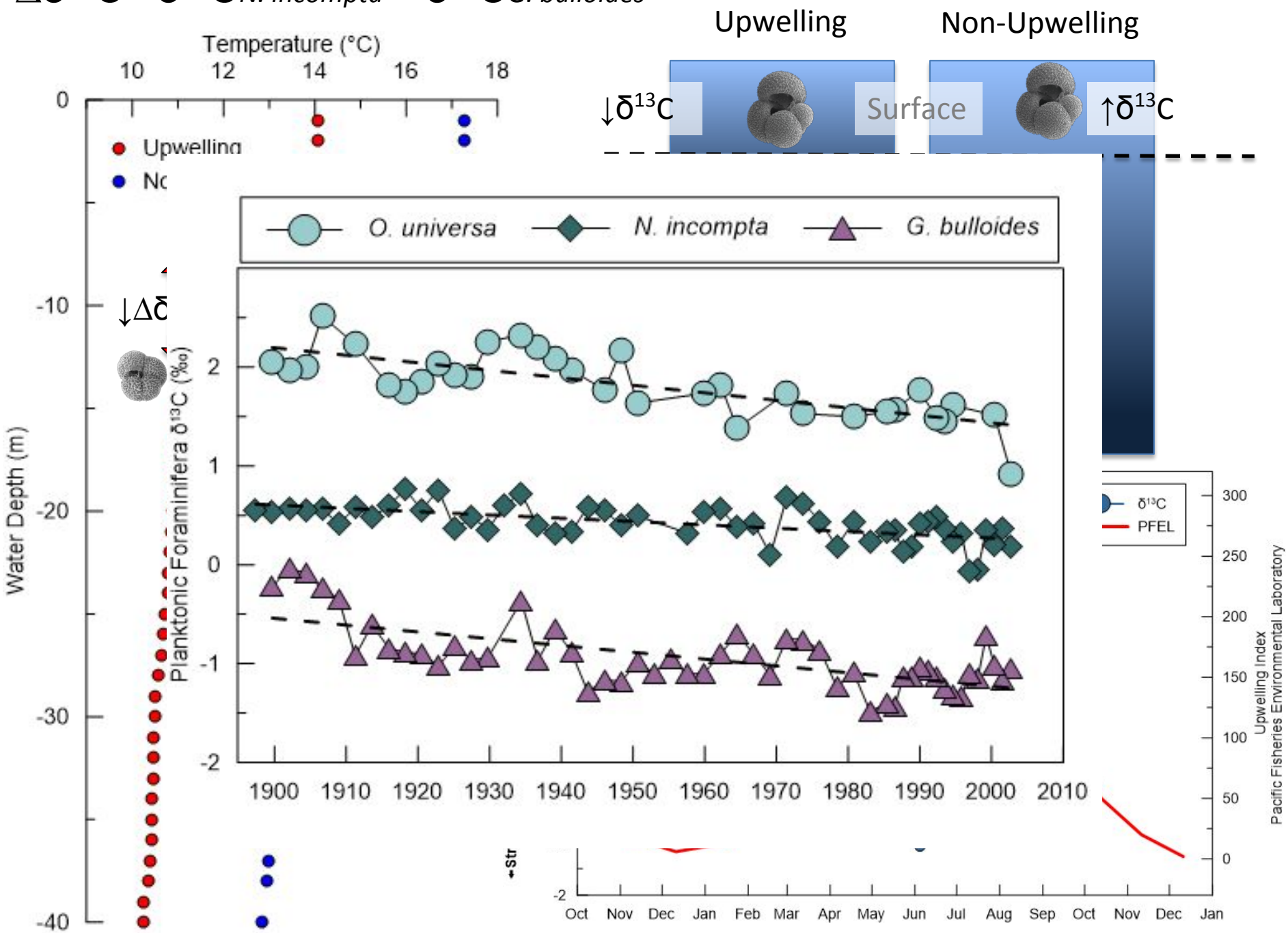
Positive (warm) PDO Phase
El Niño-Like Conditions
Weakened Upwelling

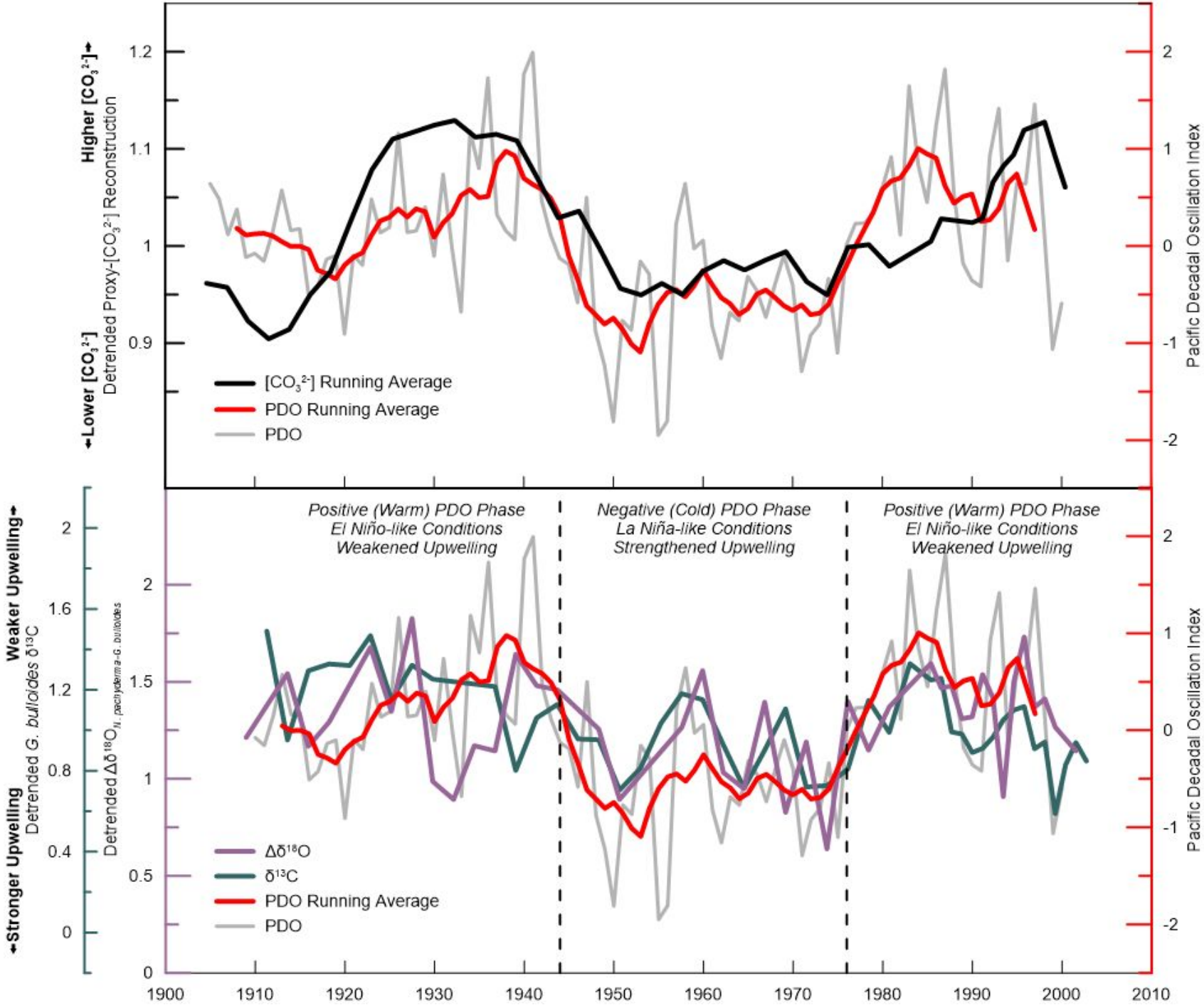
Positive (warm) PDO Phase
El Niño-Like Conditions
Weakened Upwelling



Negative (cool) PDO Phase
La Niña-Like Conditions
Strengthened Upwelling

$\Delta\delta^{18}O = \delta^{18}O_{N.\ incompta} - \delta^{18}O_{G.\ bulloides}$




Higher [CO3 2-]
Lower [CO3 2-]
Detrended Proxy-[CO3 2-] Reconstruction
Pacific Decadal Oscillation Index
[CO3 2-] Running Average
PDO Running Average
PDO
Positive (Warm) PDO Phase
El Niño-like Conditions
Weakened Upwelling
Negative (Cold) PDO Phase
La Niña-like Conditions
Strengthened Upwelling
Positive (Warm) PDO Phase
El Niño-like Conditions
Weakened Upwelling
Weaker Upwelling
Stronger Upwelling
Detrended G. bulloides δ13C
Detrended Δδ18O N. pachyderma-G. bulloides
Δδ18O
δ13C
PDO Running Average
PDO
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010

ENSO and Carbonate Chemistry

El Niño

Weakened Upwelling

Higher pH and $[CO_3^{2-}]$

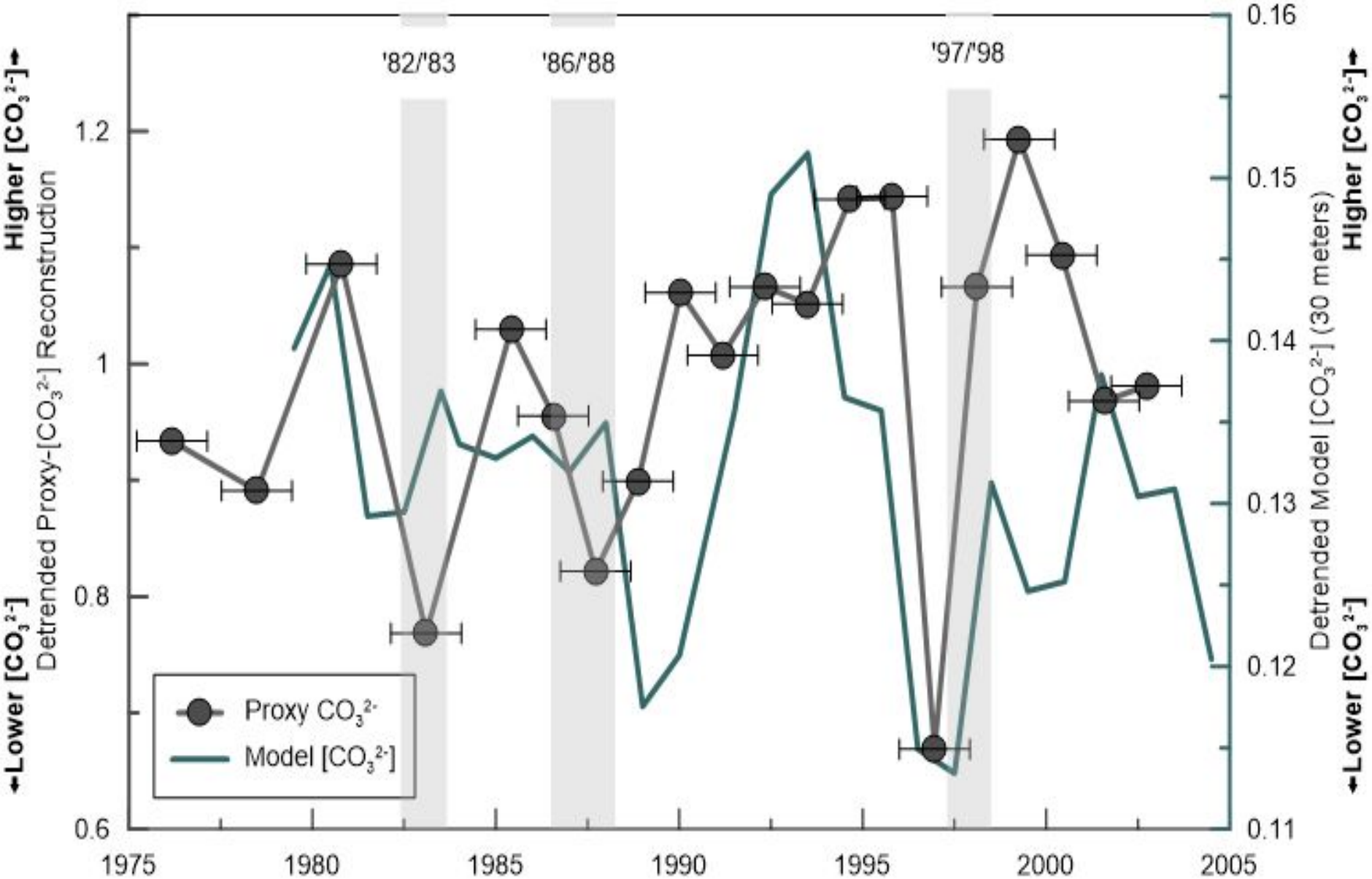
La Niña

Strengthened Upwelling

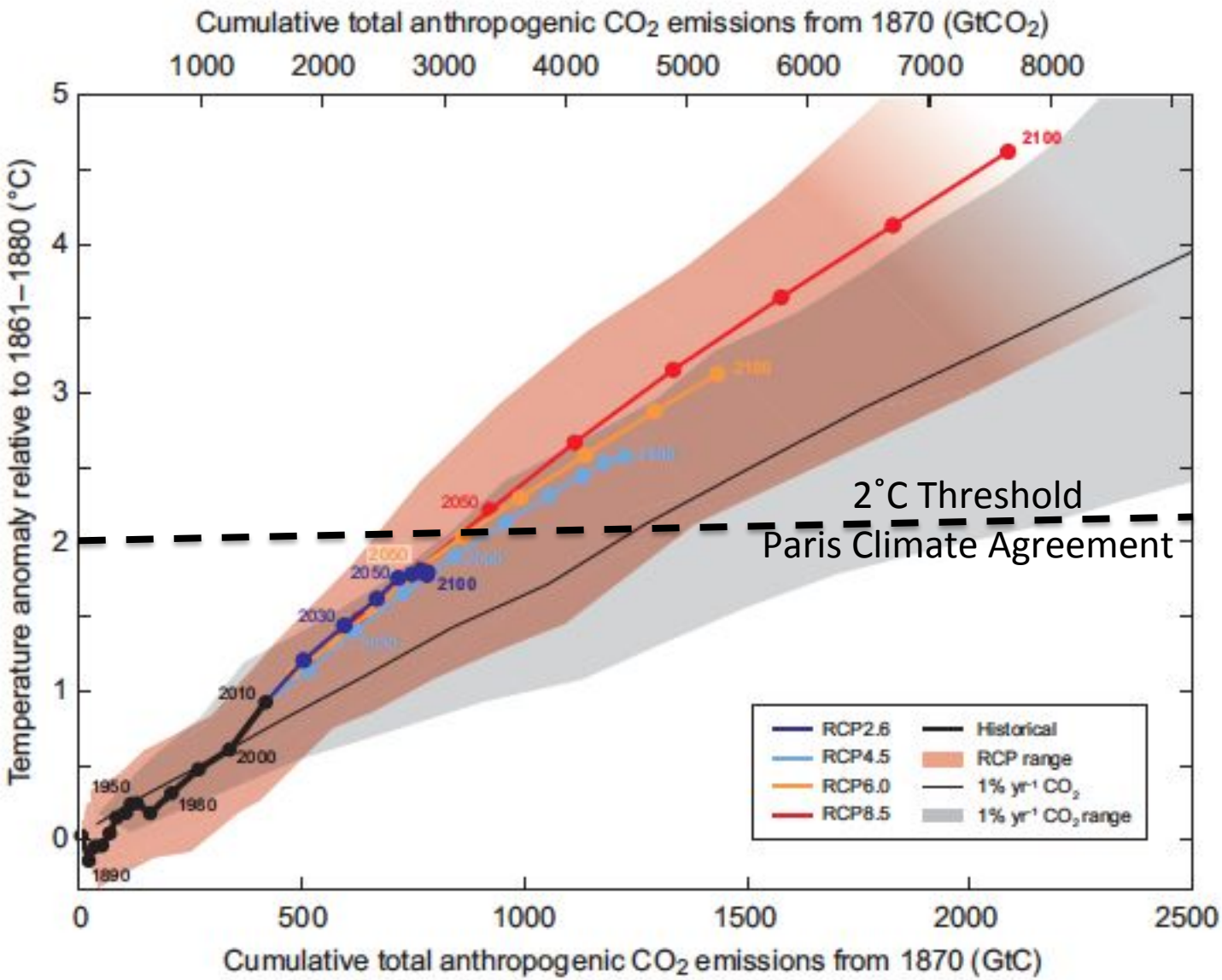
Lower pH and $[CO_3^{2-}]$

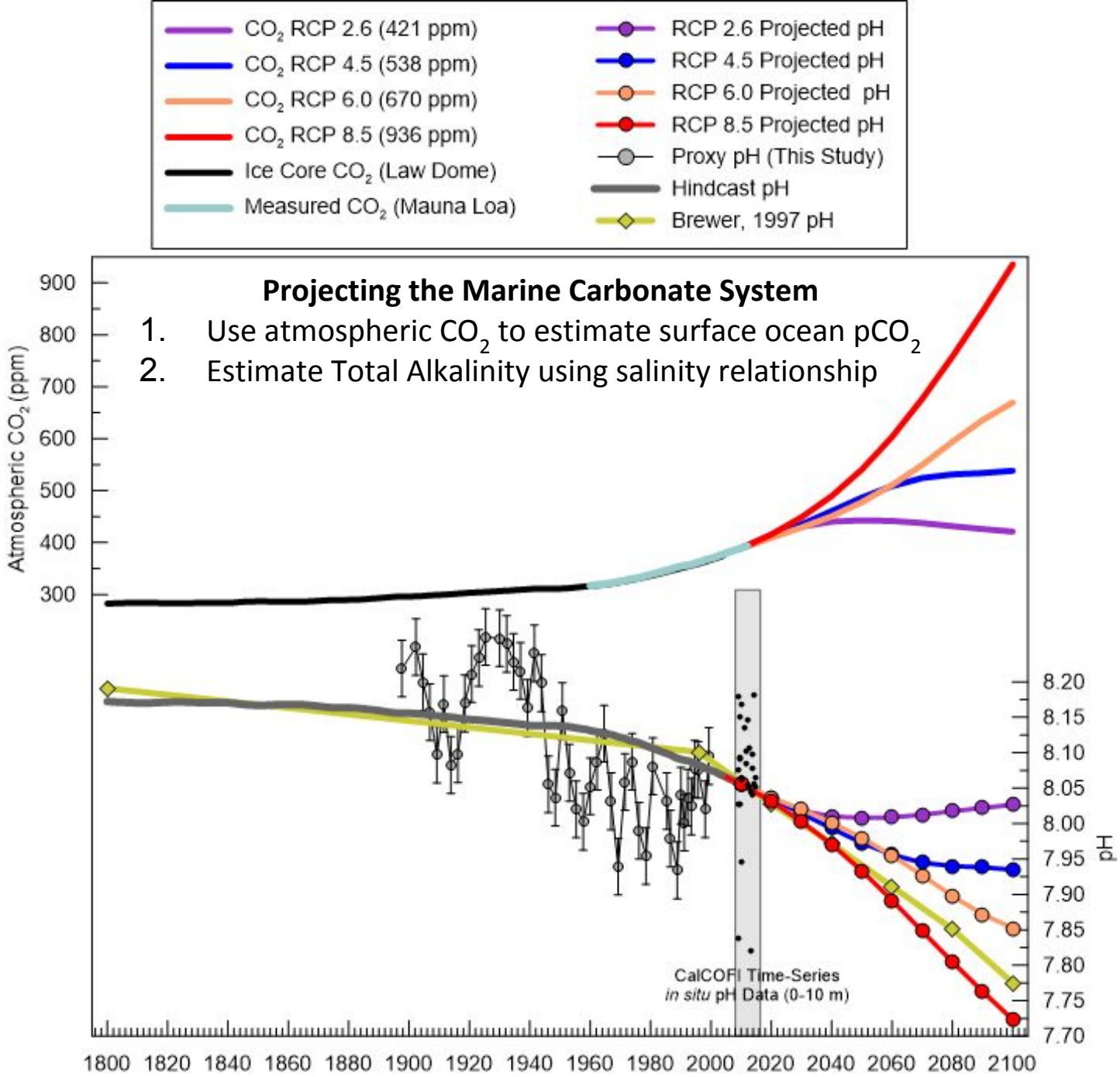
Nam et al., 2011

Anomalous **El Niño** Events



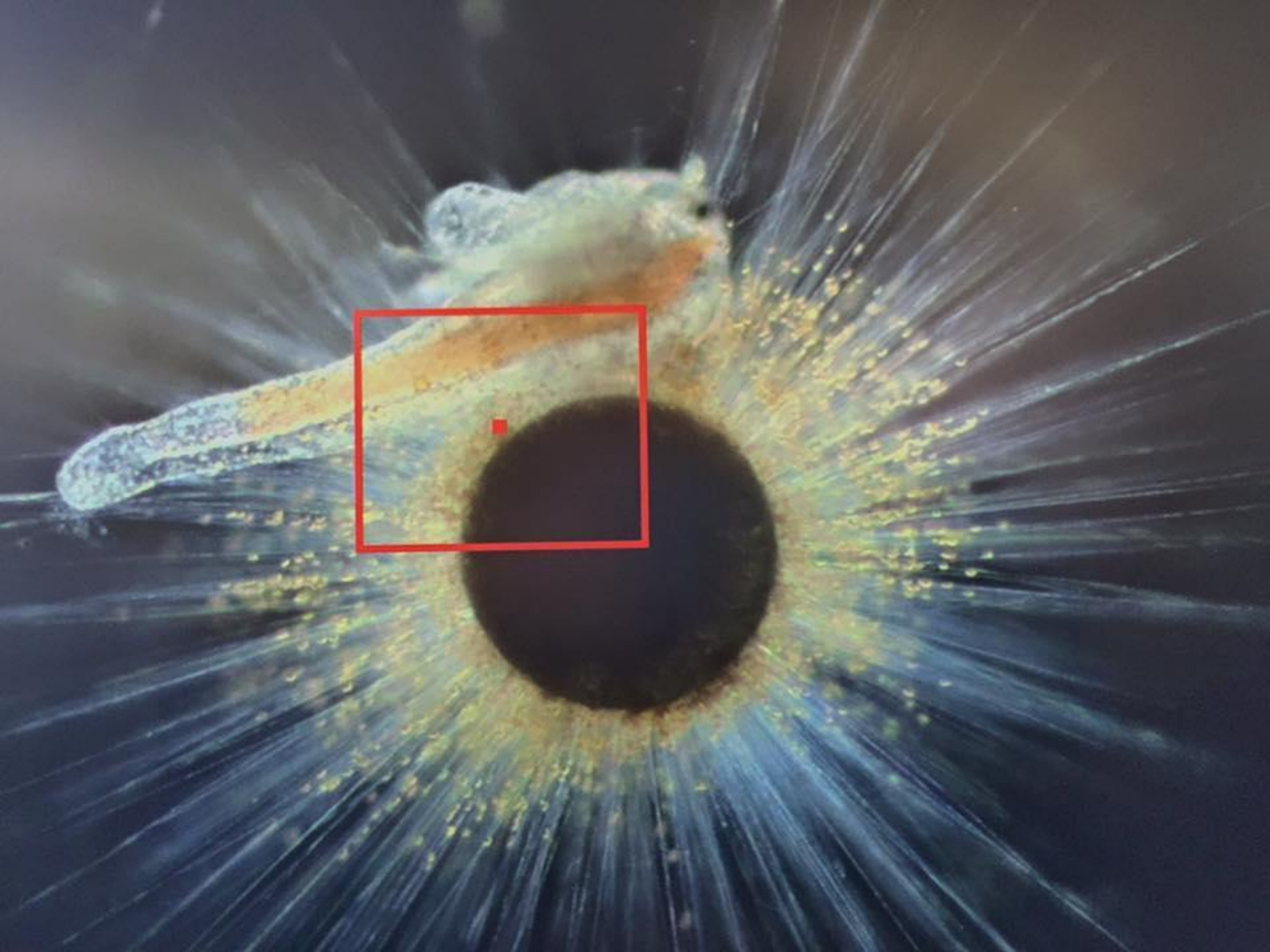
IPCC Projection Scenarios




CO2 RCP 2.6 (421 ppm)
CO2 RCP 4.5 (538 ppm)
CO2 RCP 6.0 (670 ppm)
CO2 RCP 8.5 (936 ppm)
Ice Core CO2 (Law Dome)
Measured CO2 (Mauna Loa)
RCP 2.6 Projected pH
RCP 4.5 Projected pH
RCP 6.0 Projected pH
RCP 8.5 Projected pH
Proxy pH (This Study)
Hindcast pH
Brewer, 1997 pH
Projecting the Marine Carbonate System
1. Use atmospheric CO2 to estimate surface ocean pCO2
2. Estimate Total Alkalinity using salinity relationship
Atmospheric CO2 (ppm)
900
800
700
600
500
400
300
8.20
8.15
8.10
8.05
8.00
7.95
7.90
7.85
7.80
7.75
7.70
pH
CalCOFI Time-Series
in situ pH Data (0-10 m)
1800 1820 1840 1860 1880 1900 1920 1940 1960 1980 2000 2020 2040 2060 2080 2100

Concluding Remarks

- Fossil shells of planktonic foraminifera can be used as a paleo-proxy for OA
- The OA record from the CCE indicates this region is acidifying twice as a fast as the global ocean
- Future projections indicate future emission reduction can significantly reduce OA

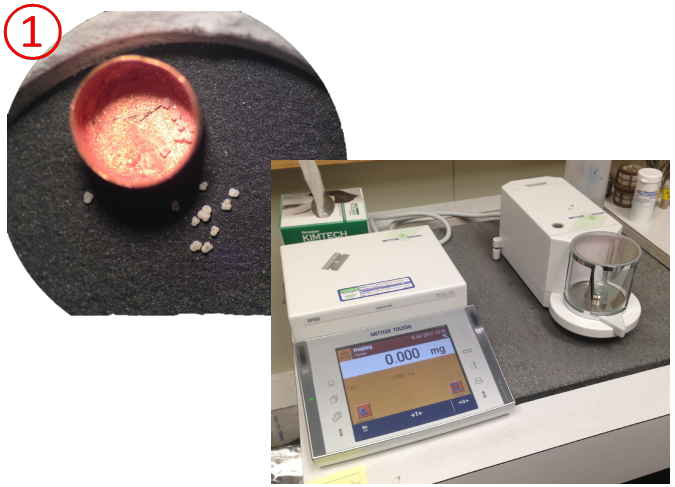


Supplementary Slides

The Area Density Method

(Marshall et al., 2013)

1



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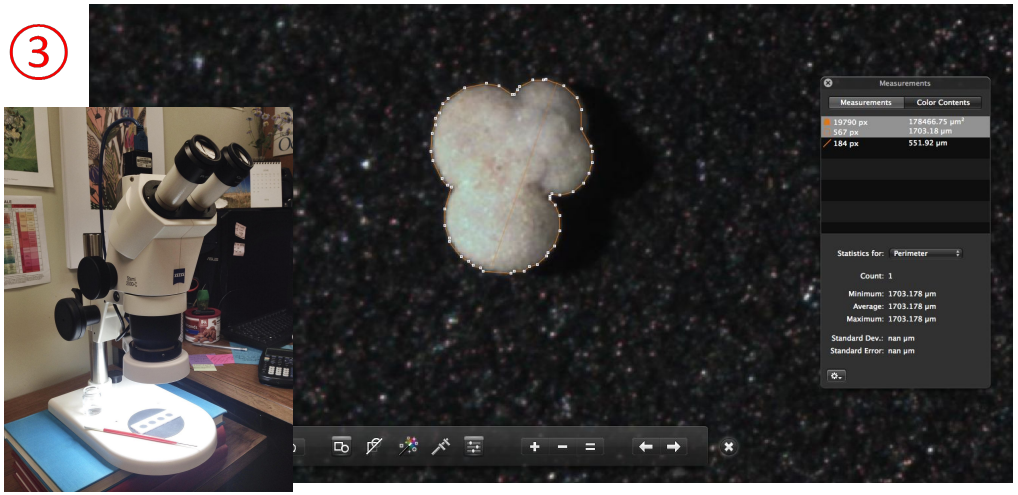
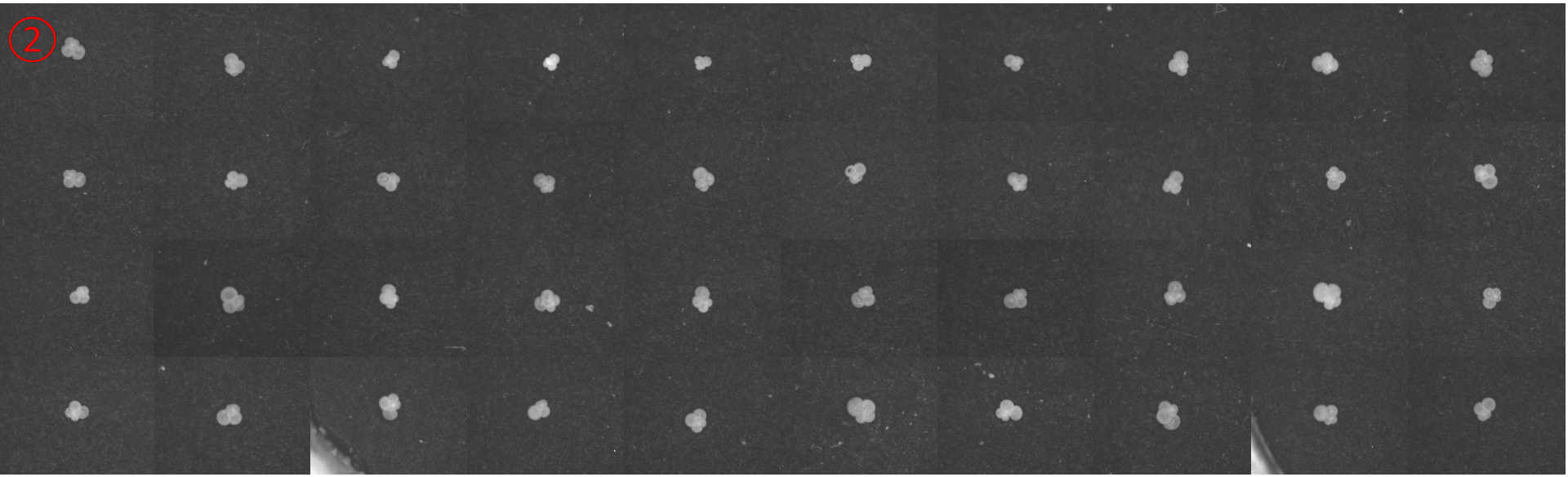
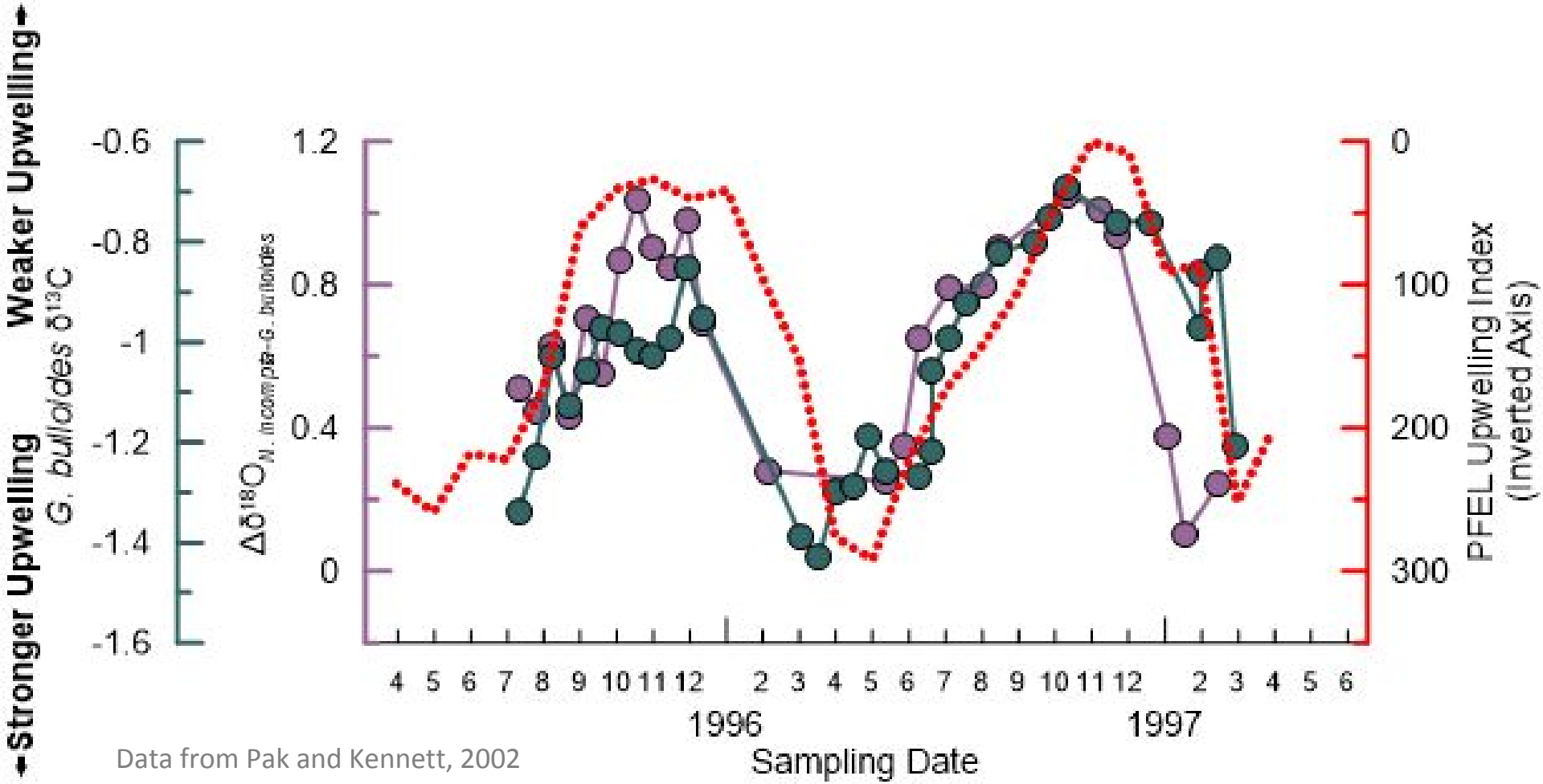


2

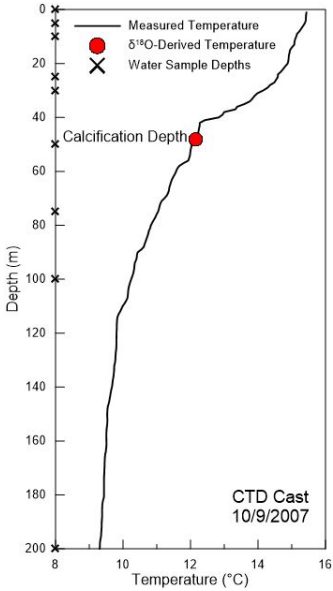


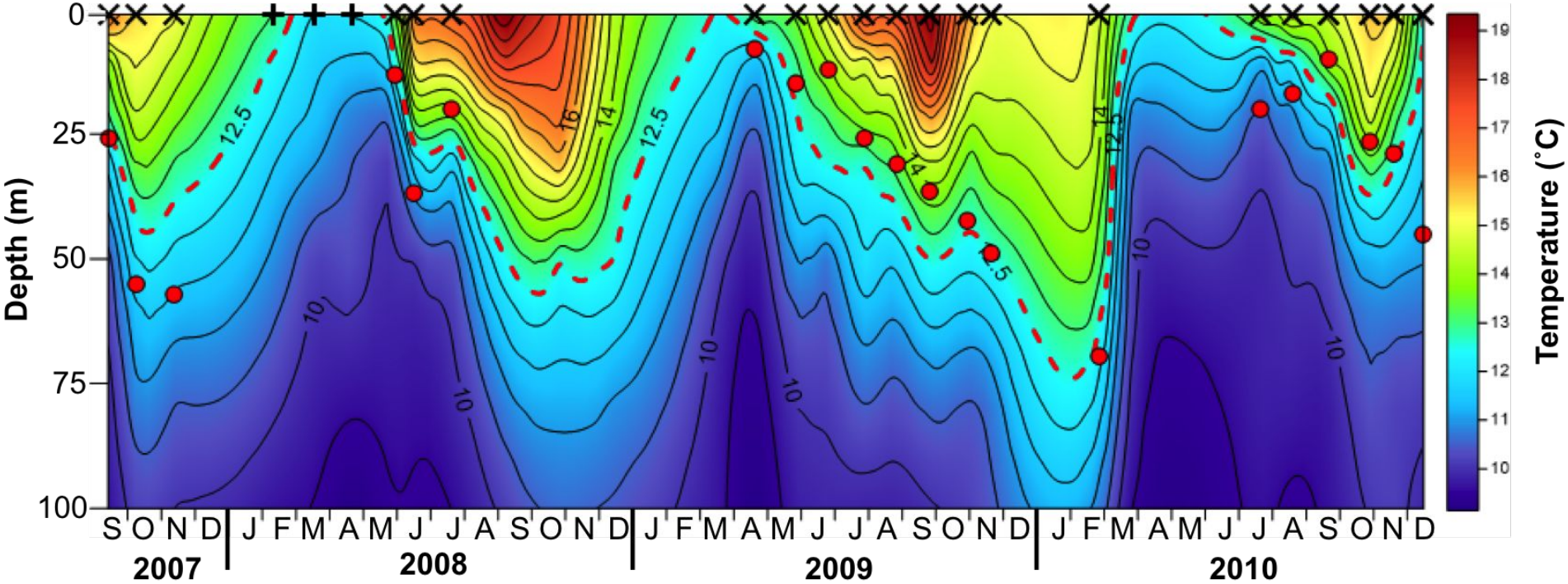
Individual Weight (µg) /Individual Area (μm^2)= Area Density ($\mu g/\mu m^2$)



Data from Pak and Kennett, 2002

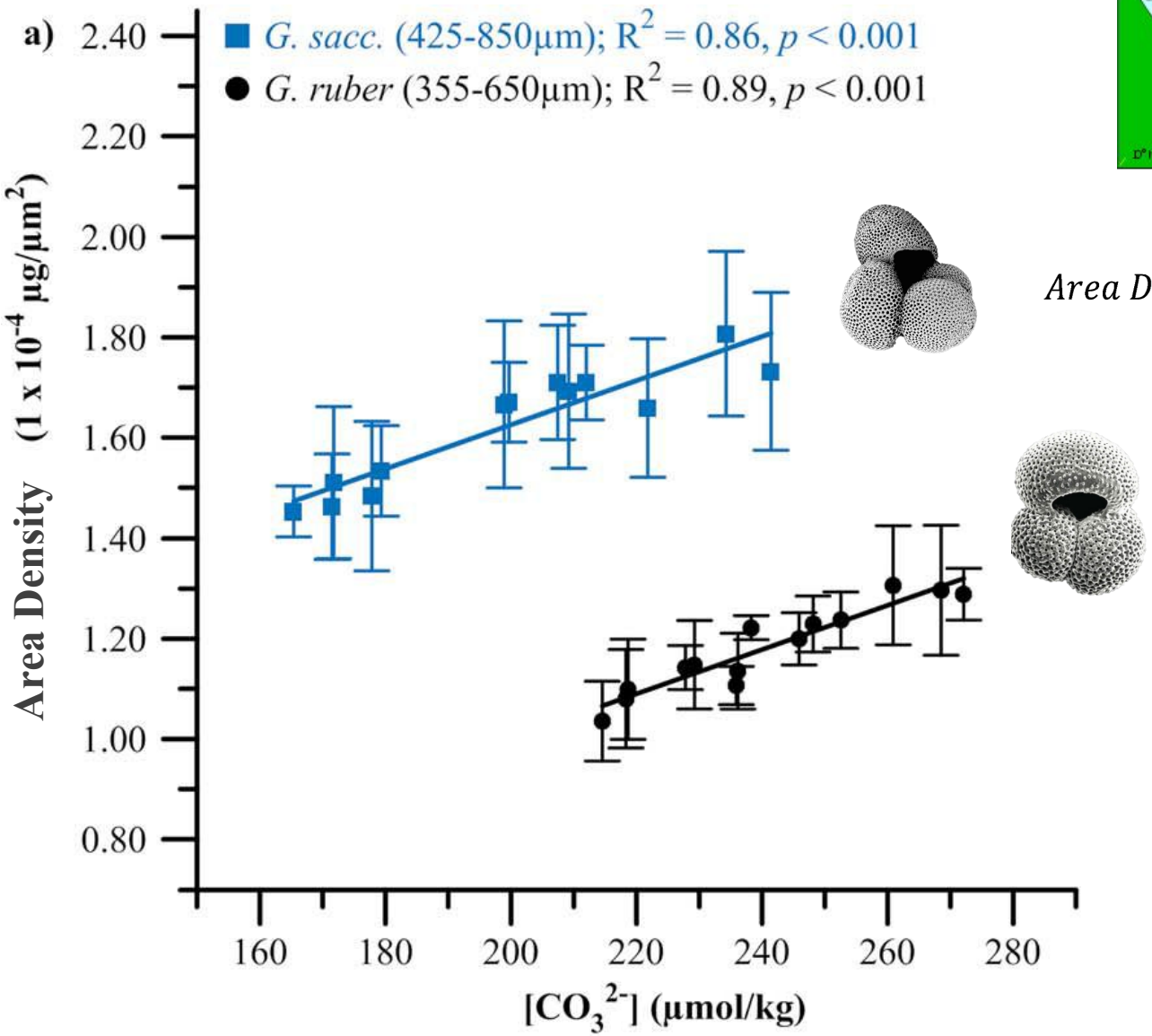
$\delta^{18}O$-Derived Calcification Depths

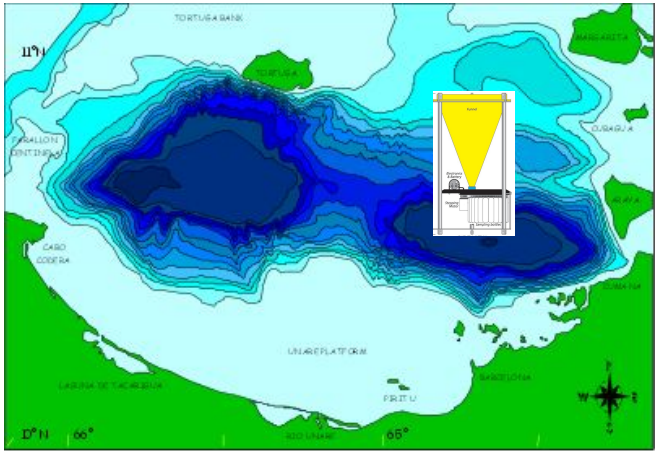




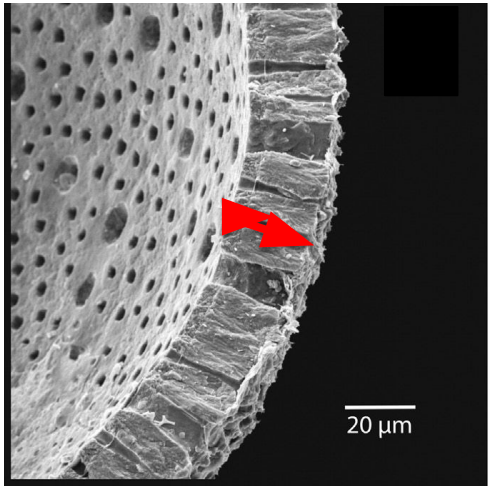
Foraminiferal Area Density

Marshall et al., 2013

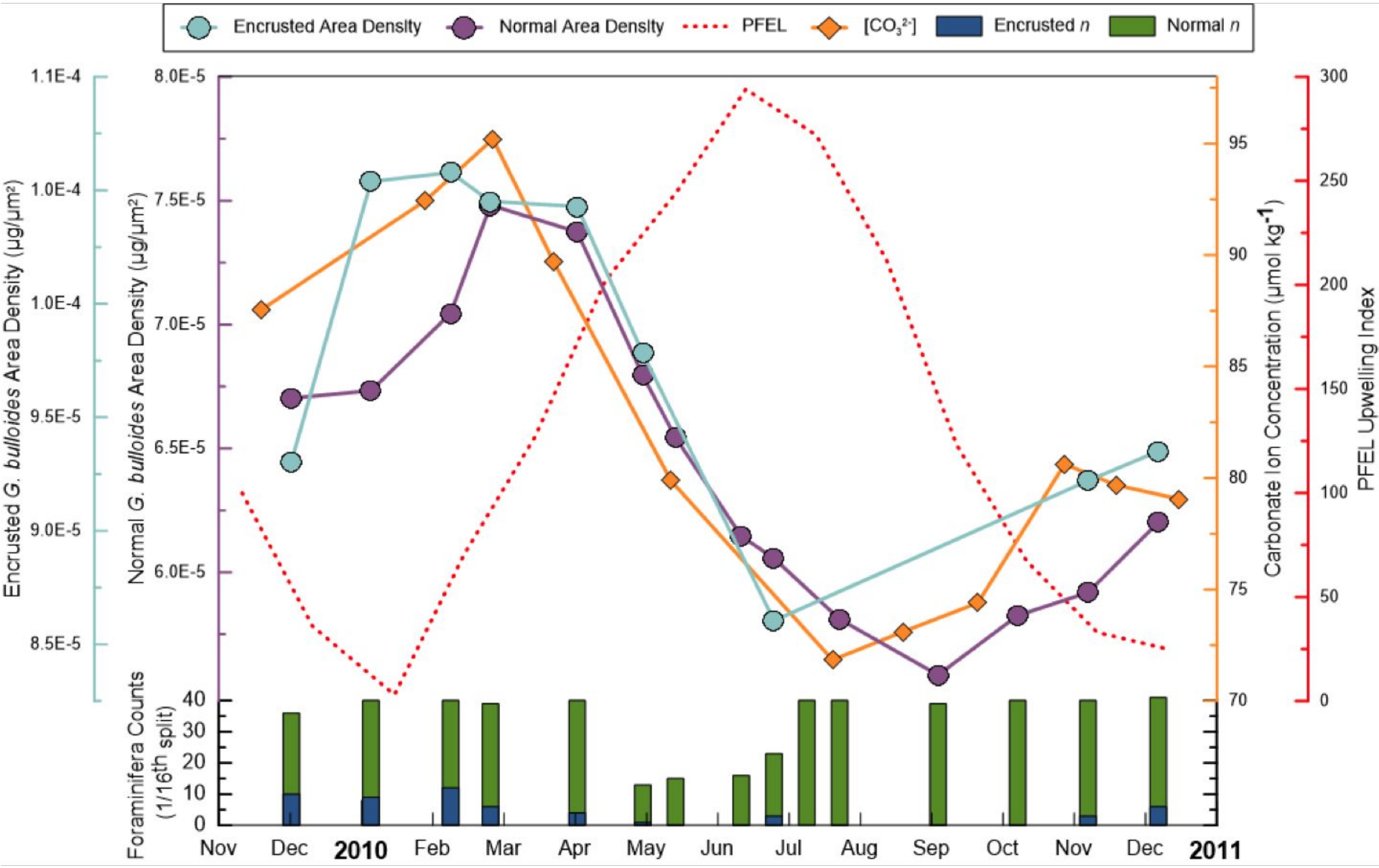




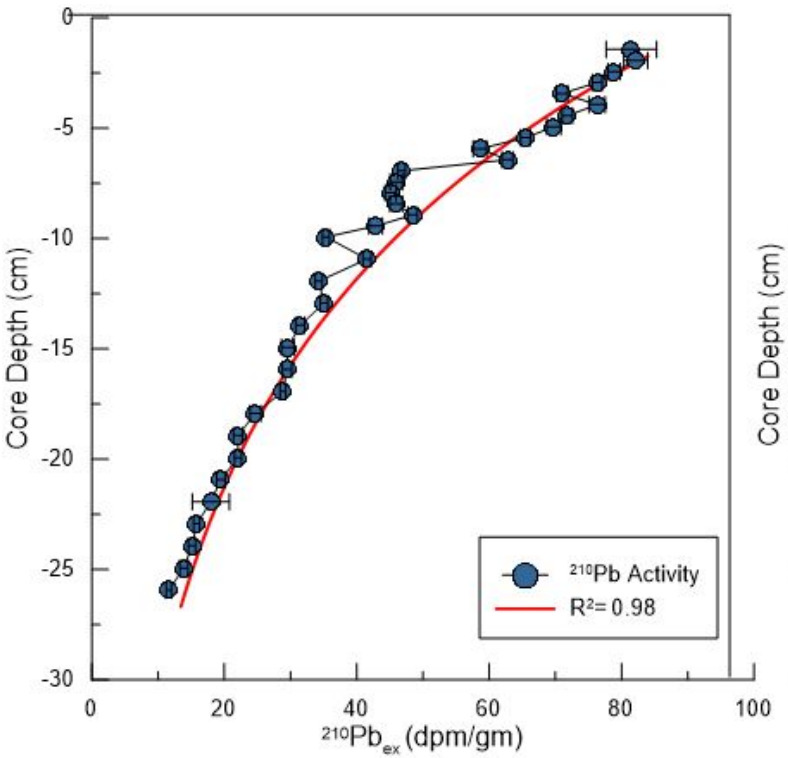
$$Area\ Density = \frac{Shell\ Weight\ (\mu g)}{2D\ Surface\ Area\ (\mu m^2)}$$

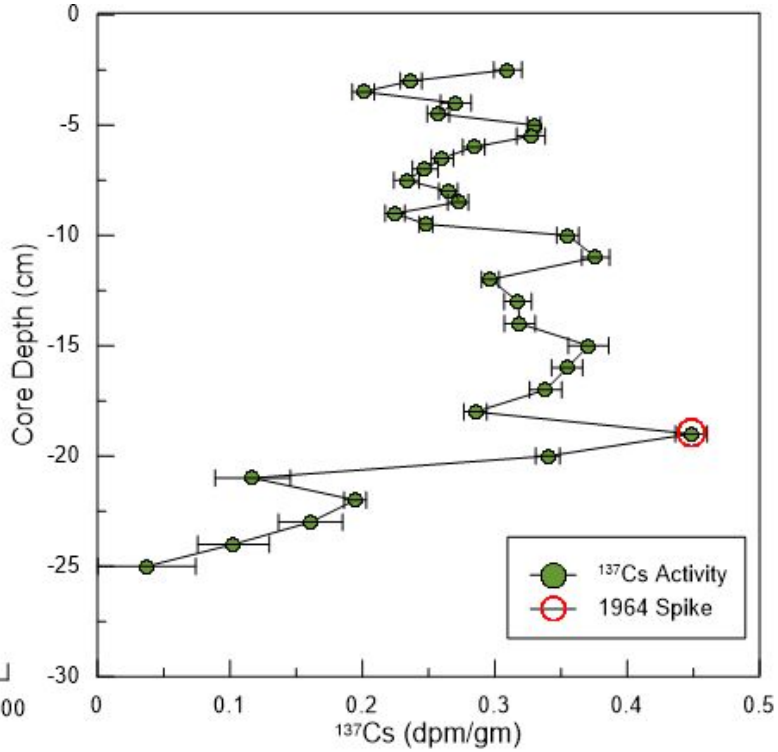


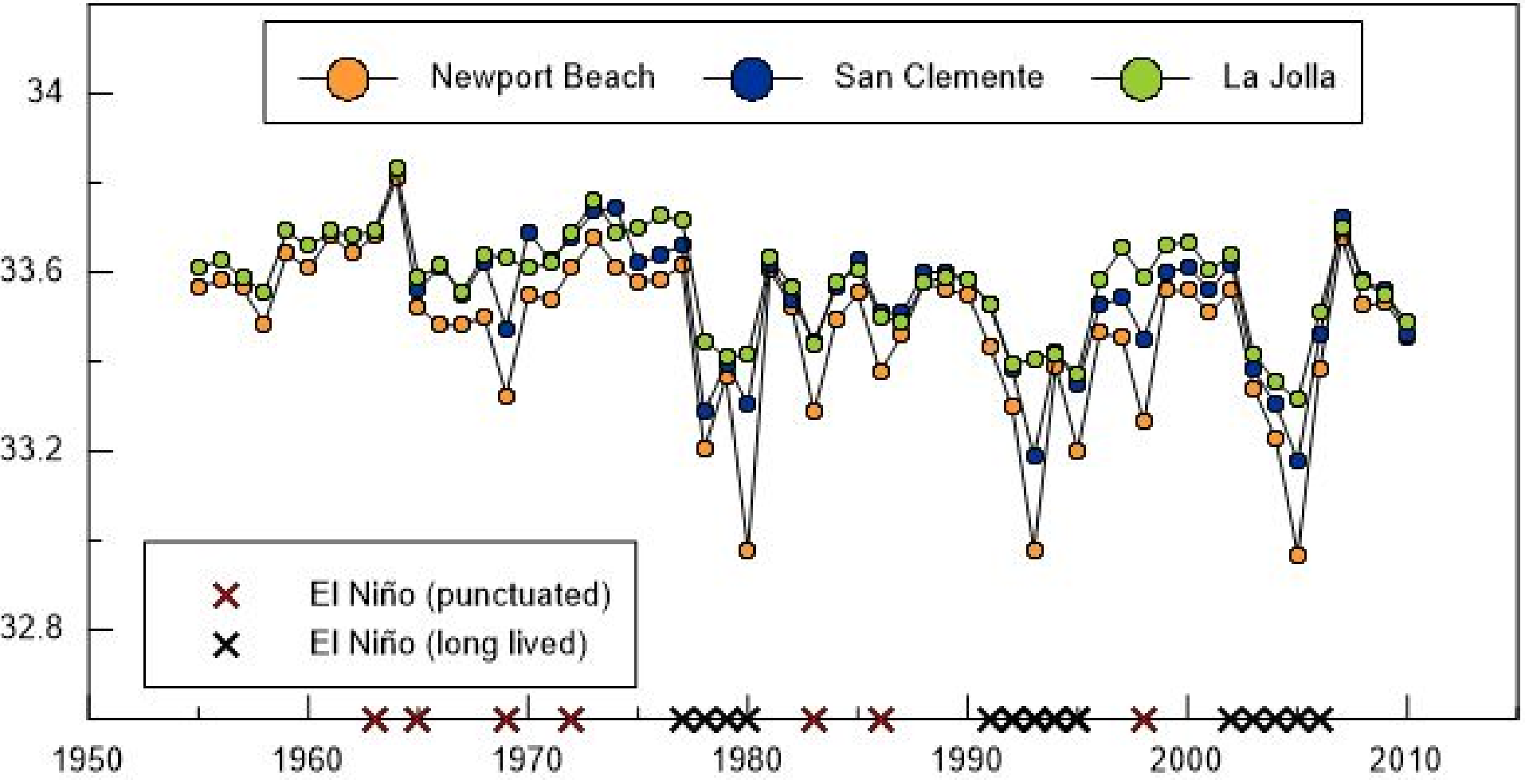
Effective Size-Normalization

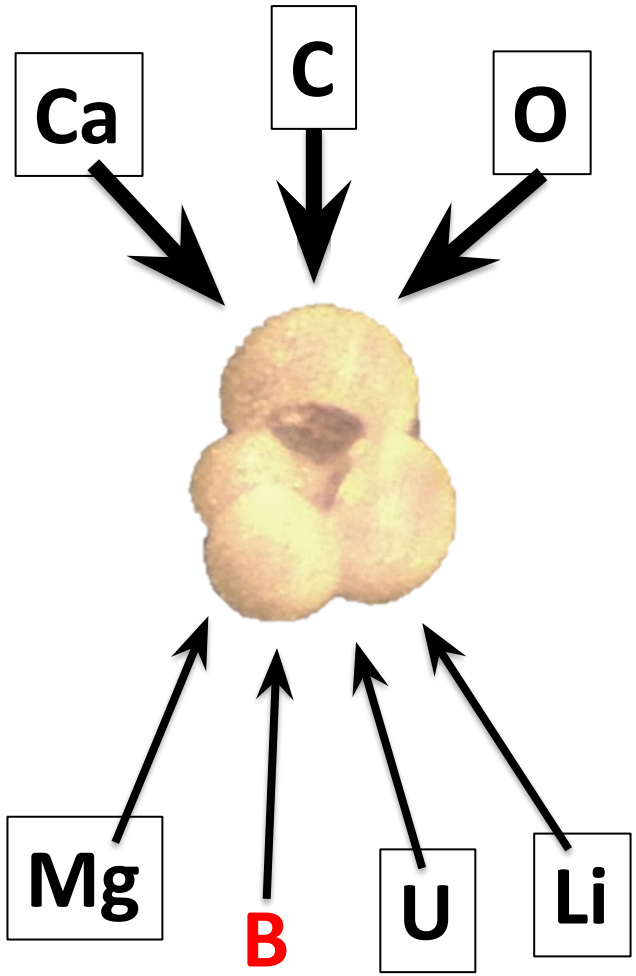
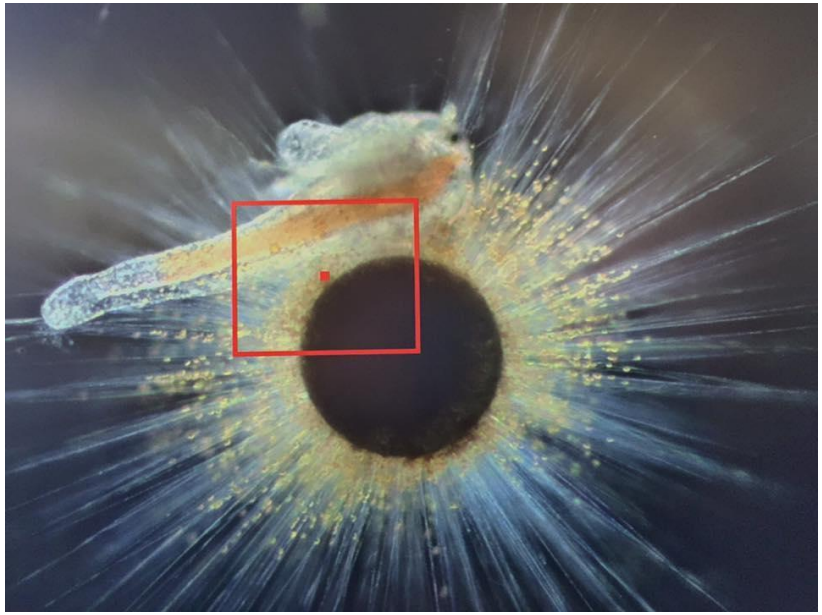

Encrusted Area Density
Normal Area Density
PFEL
[CO3 2-]
Encrusted n
Normal n
Encrusted G. bulloides Area Density (µg/µm²)
Normal G. bulloides Area Density (µg/µm²)
Carbonate Ion Concentration (µmol kg-1)
PFEL Upwelling Index
Foraminifera Counts (1/16th split)
1.1E-4
1.0E-4
1.0E-4
9.5E-5
9.0E-5
8.5E-5
8.0E-5
7.5E-5
7.0E-5
6.5E-5
6.0E-5
95
90
85
80
75
70
300
250
200
150
100
50
0
40
30
20
10
0
Nov
Dec
2010
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
2011

Age Model


Core Depth (cm)
0
-5
-10
-15
-20
-25
-30
0
20
40
60
80
100
$^{210}Pb_{ex}$ (dpm/gm)
^{210}Pb Activity
R^2= 0.98


Core Depth (cm)
0
-5
-10
-15
-20
-25
-30
0
0.1
0.2
0.3
0.4
0.5
^{137}Cs (dpm/gm)
^{137}Cs Activity
1964 Spike


Newport Beach
San Clemente
La Jolla
34
33.6
33.2
32.8
El Niño (punctuated)
El Niño (long lived)
1950
1960
1970
1980
1990
2000
2010


Ca
C
O
Mg
B
U
Li